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MEMORANDUM FOR PRS (In-House / Contractor Publication)

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SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2002-144**
Bill Hargus (PRSS) et al., "The Air Force Clustered Hall Thruster Program"

38th AIAA/ASME/SAE/ASEE JPC&E **(Statement A)**
(Indianapolis, IN, 7-10 July 2002) **(Deadline = 06 July 2002)**

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AIAA-2002-3678

The Air Force Clustered Hall Thruster Program

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Abstract

Preliminary results of the Air Force program investigating clustered Hall thrusters are presented, primarily experimental results on a cluster of four 200 W Busek BHT-200-X3 Hall thrusters. Preliminary measurements of plume current density, start transient interactions, cathode current sharing, and near exit plane magnetic fields are presented. Greatest thruster interaction occurs when cathodes are electrically connected. In a two thruster case, one cathode dominated electron emission, producing 90% of the required current. When the cathodes are electrically independent, the greatest cluster interaction occurs during a start following exposure of the thruster discharge chambers to water vapor. In this case, the thrusters enter and exit a high anode current mode related to internal plasma oscillations in a non-continuous manner. This is unlike the typical smoothly continuous anode current transient of a single thruster. Individual thrusters appear able to affect the anode current mode, and presumably the plasma oscillations, of neighboring thrusters. Once the thrusters are conditioned and if the cluster is electrically unconnected, no significant interaction is observed. Plume ion current measurements of two thrusters have yielded what appears to be a slight narrowing of the ion current density profile from that expected from linear superposition of individual thruster measurements. Near exit plane magnetic field measurements indicate that the magnetic fields between the thrusters are affected by neighboring thruster magnetic fields. As such, the near plume electric fields would also be modified and may be responsible for apparent plume narrowing.

Introduction

At the present time, electric propulsion is used by an increasingly large fraction of commercial space vehicles. By virtue of reducing station-keeping propellant mass, it has become the economic alternative to chemical propulsion. The US Air Force has also begun to consider manifesting electric propulsion on missions such as the Advanced EHF communications constellation.

Long term Air Force Space Command goals include the introduction of orbit transfer vehicles and rescue vehicles capable of salvaging satellites placed in incorrect orbits [1]. These missions can only be implemented by using propulsion systems with the specific impulses delivered by electric propulsion. Currently, both Hall thruster and ion engine propulsion technologies being considered for this role.

For Air Force missions, Hall thrusters have the ideal combination of high thrust density and ruggedness combined with a thrust efficiency generally greater than 50%. It is likely that Hall thrusters will be increasingly manifested on large Air Force space assets. The thrust levels available to high power Hall thrusters and the reliance of the military on space based resources are portents of for greater numbers of high mass, high value space assets. Some of these high mass missions will only be enabled through the use of high specific impulse propulsion for orbit repositioning, orbit raising, and/or circularization.

As Hall thrusters grown geometrically larger, they are inherently more efficient due to inherent plasma scaling within the main discharge [2]. Greater uniformity of the radial magnetic field, lower internal plasma densities, and fewer wall losses improve performance as geometrical size increases. Furthermore, lifetimes improve as thrusters increase in size (and subsequently power). Lower plasma densities result in fewer sputtering wall collisions, hence a longer insulator lifetime.

Larger thrusters are more susceptible to ingestion of background neutrals, and require more stringent vacuum levels to be properly ground tested. If a vacuum level of 5×10^{-5} Torr is acceptable for a 1 kW thruster [3], a similar ratio of internal acceleration channel density to background density for a 100 kW thruster would require a background pressure approximately an order of magnitude lower at 5×10^{-6} Torr (assuming a constant 300 V discharge). The pumping speed of a chamber capable of testing a 100 kW thruster would then have to increase by three orders of magnitude over that required by a 1 kW thruster due both to an increase in propel-

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lant flow rate and the stricter vacuum requirement. The minimum pumping speed required would then be on the order of 10,000,000 l/s on xenon, approximately an order of magnitude higher pumping speed than the largest available US facilities. Even if such a facility were available, a lifetest of a 100 kW class Hall thruster would be extremely expensive and would require the dedicated use of this currently nonexistent facility.

A cluster of lower power Hall thrusters has several advantages over a monolithic propulsion design. Once a single 'building block' design is constructed and qualified, it will be relatively simple and inexpensive to produce any reasonable power level by the simple expedient of adding more thrusters. It is also significantly cheaper and more timely than constructing and qualifying new thrusters for successive missions.

The modular design philosophy is also more robust and able to tolerate individual failures while retaining propulsive capability. A satellite with a single monolithic thruster is less reliable than a cluster with inherent redundancy. A high power Hall thruster system using a single monolithic thruster has an intrinsic single point failure.

The general inability of Hall thrusters to throttle efficiently over a wide range of powers is also considered. A cluster is able to throttle through a variety of power/thrust levels more efficiently than a monolithic thruster operating at off design conditions. Of course with increasing satellite bus powers, any design philosophy advocating clusters will still demand that larger thruster designs be developed so that they may be incorporated into still larger clusters as spacecraft power levels continue to rise.

In response to these trades, the Air Force Research Laboratory has chosen to study the aspects related to clustering Hall thrusters in order to cost effectively reach combined thruster powers of 100 kW while minimizing total life cycle costs. The details of the design analysis are presented in more detail elsewhere [4].

Program Overview

The AFRL clustered Hall thruster program consists of several distinct components. Thruster development is currently being performed at Busek Co. under several SBIR programs. Recently, a cluster of 200 W Hall thrusters has been delivered to AFRL for preliminary cluster research. A second cluster at intermediate power (600 W) is being developed to examine issues such as cathode current sharing, electrical cross-talk, and plume interactions.

AFRL is collaborating with the University of Michigan, Ann Arbor, to construct a high power cluster of 5 kW class P-5 thrusters [5]. These jointly developed thrusters will be delivered to the university in late 2002. Currently, modeling efforts are underway to anticipate the introduction of the cluster of P-5 Hall thrusters into the University of Michigan vacuum facility [6,7].

AFRL is also collaborating with Stanford University examining the use of arcjets as neutralizers for clusters of Hall thrusters [8]. This effort has demonstrated the neutralization of a Hall thruster using low power helium and hydrogen arcjets. Additional efforts are being directed toward the development of non-intrusive diagnostics especially for plasma density measurements which have applications for electric propulsion.

At AFRL, an array of 200 W Busek BHT-200-X3 Hall thrusters has been tested for several hundred hours. A paper will be presented detailing plume interactions [9]. Another paper will detail a thruster start-up transient that can also affect cluster operations [10]. Other measurements of the cluster of BHT-200-X3 Hall thrusters, including flux measurements, electrical cross-talk, and cathode current sharing, will be presented in this work.

Facility and Thrusters

These measurements were taken in Chamber 6 at the Air Force Research Laboratory (AFRL) Electric Propulsion Facility at Edwards AFB, CA. Chamber 6 is a stainless steel chamber with a 1.8 m diameter and 3 m length. It has a measured pumping speed of approximately 32,000 l/s on xenon. Pumping is provided by four single stage cryo-panels and one 50 cm two stage APD cryo-pump. The chamber is roughed by a oil free Stokes Stealth® mechanical pump and blower.

The thrusters used for this test are four BHT-200-X3 thrusters which are individually described in detail elsewhere [11]. This is a cluster of four 200 W thrusters being tested to determine the engineering aspects of clustering higher power Hall thrusters on a single spacecraft. The BHT-200-X3 Hall thruster was chosen due to its availability from the TechSat-21 program, and the reasoning that due to the smaller size and hence higher plasma densities, the 200 W thrusters would produce the maximum possible interaction. The cluster of four thrusters is shown in Fig. 1. The thrusters are placed in a 2x2 grid with a center-to-center separation of approximately 114 mm.

Each BHT-200 in the cluster is independently connected to four Sorensen power supplies. A DHP-400-5 is used for the main discharge, a DCS-600-1.7E is used to power the cathode keeper, and two DLM-40-15 provides power to the cathode heater and magnetic circuit. During testing the thruster was run at the nominal conditions shown in Table 1. Following exposure of the thrusters to ambient atmospheric conditions, the cathodes of each thruster are conditioned by flowing 1 sccm (98 μg/s) of xenon and heating for approximately 90 minutes.

An inductive-capacitive (L= 250 μH, C = 13 μF) filter is placed between the anode and cathode external to the chamber. This filter approximately duplicates the impedance characteristics of a power processing unit (PPU) for the BHT-200. The aim of the circuit is not to attempt to replicate PPU characteristics, but to provide isolation of the power supplies from the discharge oscillations of the plasma and to insure that any oscillations are not a product of feedback between the power supplies and plasma.

Table 1: Nominal Thruster Operating Parameters

Anode flow	840 μg/s
Cathode flow	98 μg/s
Anode potential	250 V
Anode current	830±10 mA
Keeper current	0.50 A
Magnet current	1.0 A
Heater current	3.0 A

Xenon propellant (99.995%) flow to the thrusters is controlled by use of Unit Instruments model 7301 digital mass flow controllers (MFC) calibrated for xenon. Flow for each anode and cathode is individually metered through a separate MFC. For each thruster, ten electrical operating parameters are recorded during operation of the system using

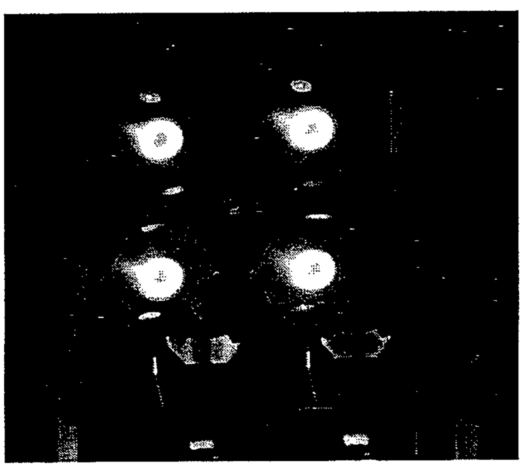

Fig. 1. The cluster of BHT-200 Hall thrusters firing within AFRL Chamber 6. The thrusters are numbered 1 through 4 starting from the upper left corner and proceeding counter-clock-wise.

an Agilent 34970A data acquisition and switch unit. These parameters include the currents and potentials of the anode, cathode, heater, keeper, and magnet circuits. These data are taken at approximately 1 Hz.

Measurements and Analysis

The cluster was delivered to AFRL approximately 1 year ago. During this time, a number of measurements have been performed including a series of preliminary measurements which explore issues, such as plume interactions and plasma cross-talk, related to clustering Hall thrusters. Several of the more detailed measurements are presented in greater depth in companion papers [9,10].

Plume Current Density

A molybdenum guarded Faraday probe was used to measure the ion current exhausted by the cluster. The probe is described in detail elsewhere [12]. The probe and guard ring were biased 30 V below chamber ground, approximately 18 V below the cathodes which flowed freely at approximately -12 V. The current was measured using a second Agilent 34970A data acquisition and switch unit which allowed 22 bit measurement of the probe current through an internal precision 5 Ω resistor.

The probe was placed at the end of an arm 60 cm from the thruster exit plane. The arm was mounted onto a rotary stage that allowed the probe to rotate through the plume, 0-180°. The center of rotation of this first rotary stage was placed directly below the center of the exit plane of thurster 3. A second rotary stage was placed below the probe to allow the probe rotate about its front face center axis. The probe and rotary stage locations in shown in Fig. 2.

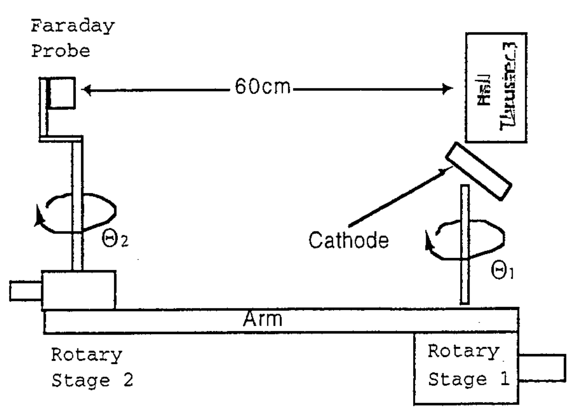

Fig. 2. Schematic of Faraday probe system at Θ_1 = 90° and Θ_2 = 0°. Angular directions and position relative to thruster 3 are also shown.

Figure 3 shows a profile of the ion current density as measured by the Faraday probe for thruster 3 only. Two sets of data are shown. The upper curve shows current density of the probe facing toward the thruster ($\Theta_2 = 0°$), while the lower curve gives the flux of the probe when it is facing 180° away from the thruster ($\Theta_2 = 180°$). The $\Theta_2 = 180°$ data provide an indication of the uncertainty in the random ion current flux measured by the shielded Faraday probe. Near the center line, the reversed probe measures approximately 1% of the front facing probe current density. In the fringes, the reversed probe measures nearly 25% of the forward facing probe. This greater uncertainty in the fringes is important to note due to the increased weighting given to the periphery by the spherical symmetry of the plume measurement.

Another measurement of the relative uncertainty of the current density measurements of Fig. 3 is illustrated by the integration of the profile. This yields a total beam current of 742 mA. The flow rate through the thruster anode is 8.5 sccm (840 μg/s) [13]. If each xenon neutral which entered the thruster is singly ionized, the total current beam current would be an estimated at 614 mA. In this case, the measured beam current is approximately 121% the estimated beam current.

The assumptions of 100% propellant utilization and that the propellant is only singly ionized are not necessarily true. A fraction of the xenon atoms will not be ionized and will escape the thruster. Measurements of thrust, ion velocity, and neutral velocity however indicate that this fraction is no greater than 10%. So the assumption of 100% propellant utilization, while simplistic, is not far off the mark. Measurements by Gulczinski of charged species fractions in the near and far plumes of a 5.3 kW thruster indicate that substantial multiply charged xenon ions are present in the plume [14]. In these measurements of the near plume (10 cm) 37% of the

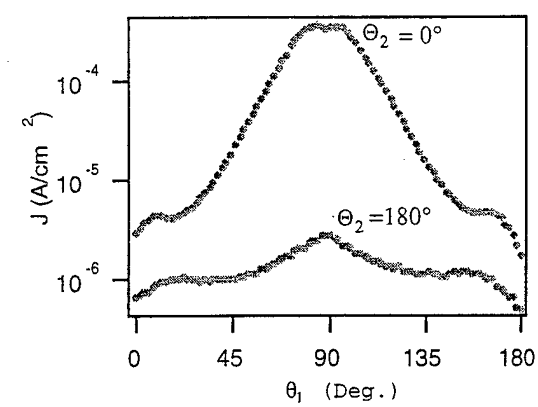

Fig. 3. Current density measurement of thruster 3 for $\Theta_2 = 0°$ (probe facing toward thruster), and $\Theta_2 = 180°$ (probe facing 180° away).

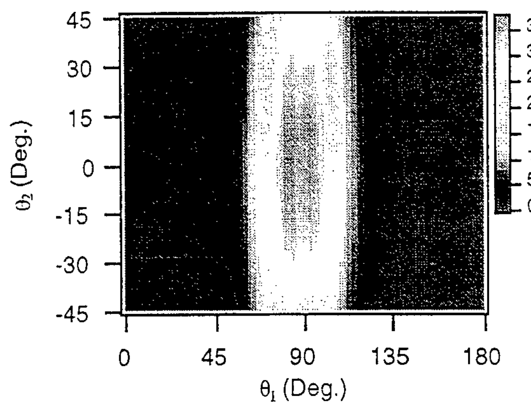

Fig. 4. Plot of ion current (μA/m^2)in the plume of thruster 3varying the probe orientation to the thruster (Θ_2).

ions are doubly charged or greater, including 3% that were quadruply charged. In the far plume (75 cm), only approximately 8% of the ions were doubly, or greater, charged. Assuming 100% utilization, Gulczinski's thruster would have measured beam currents of 110 to 150% higher than that assuming only singly ionized ions.

Although uncertainties such as secondary electron emission from the Faraday probe surface can not be discounted, the measurements appear to be consistent with what is expected from a thruster producing multiply charged ions. The production of which is made all the more likely by the lower power BHT-200. Scaling of these devices dictates a significantly higher plasma density within the thruster, and therefore, a greater opportunity for collisions which create multiply charged ions.

Figure 4 shows a contour plot of the measured current density of thruster 3 where in addition to the rotation of the probe arm (Θ_1) through the plume, the second rotary stage under the probe (Θ_2) was varied from ±45°. The symmetry of the results about the Θ_2 axis show that the expansion is approximately radial and the current density will exhibit an R^{-2} dependency in expansion.

Similar Faraday probe measurements were performed on thruster 2, with and without thruster 3 operating. In all these cases, the Faraday probe remained aligned to thruster 3 as previously described. Figure 5 shows a plot of the measured current densities for three cases: thruster 3 only, thruster 2 only, and thrusters 2 and 3 simultaneously. Additionally, a computed curve of current densities of thrusters 2 and 3 added together is shown.

The data for thruster 2 show a characteristic curve similar to that of thruster 3 which are also shown in Fig. 3. The difference between the current density data is due to the alignment of the probe on thruster 3. Therefore, the peak current density for the thruster 2 measurement is displaced by 15° due to the probe angle ($\Theta_2 = 0°$) and the 110 mm (thruster separation) shift in the plasma source. When both thrusters 2 and 3 are operated, this shift is only approximately 5° due to the superposition of the plumes.

A check of the linearity of the plume superposition is shown in Fig. 5. Here, we see that the plume current densities of thrusters 2 and 3 during simultaneous operation do not exactly match the sum of the individually measured current densities. The calculated peak values near the plume center line are 12% lower than the measured value. This contrasts with the fringes where, for example, 60° away from center line, the estimated current density is approximately 20% greater than that measured. This data implies that while the linear superposition of two plumes is in rough agreement with experiment, the simultaneous operation of thrusters 2 and 3 produces an unexpected narrowing of the combined plume over that expected by the simple superposition of the plumes.

Several cautions need to be considered in the analysis of Fig 5. The most important of which is the interaction of the probe with the plasma. The data produced by Faraday probes should at best be considered a figure of merit. This is due to the simplistic analysis of Faraday probe data where we have neglected the effect of the probe on the plasma flow and the secondary electron yield of the probe face. For instance, it may be argued that the increased plasma density when thrusters 2 and 3 are operating affects the probe

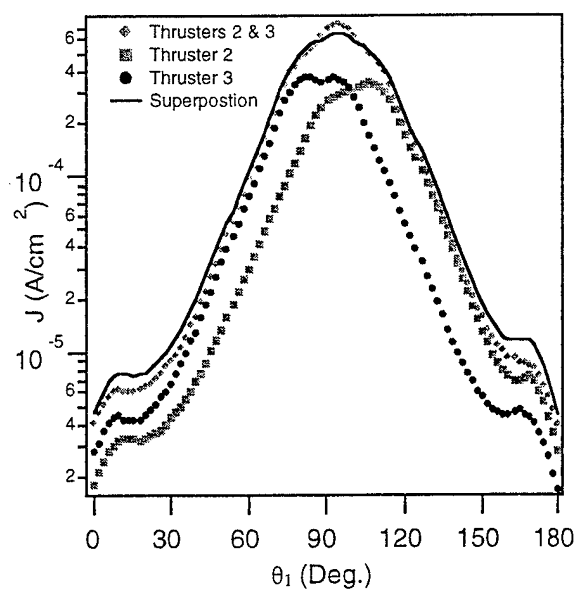

Fig. 5. Plot of ion currents ($\Theta_2 = 0°$) for thrusters 2 and 3, individually and combined. The linearly added data from the single thruster measurements is also shown.

response. This is initially counter-indicated by the lowered measured current density in the wings. It is important to note that the differences only imply a modification of the combined plumes. Further measurements are planned which will use an emissive probe to measure the plasma potential to determine whether the electric fields in the plume are modified by adjacent thrusters.

Start Transient

During the initial operation of the cluster, it was discovered that oscillations of individual thrusters were linked to other thrusters in the cluster. Specifically, during the first 5 to 10 minutes of operation, thrusters would enter and exit a high current mode where the anode current would be up to 50% higher than the nominal values given in Table 1. Thrusters in the cluster would exit the high current mode as others entered, or a single thruster would enter and leave the high anode current mode without connection to the other thrusters in the cluster. Figure 6 shows the traces of anode currents of the four thrusters in the cluster as they variously enter and exit this high current mode.

After operating for times greater than approximately 7 minutes, the behavior ceased and upon restart did not manifest itself again. The behavior reappeared if the thruster was exposed to atmosphere or to gases regenerated from the cryogenic pumping surfaces. A plot of a single thruster start after exposure of the thruster to atmosphere is shown in Fig. 7. It shows what is generally a very repeatable behavior. The initial anode current spike (1.5 A) is due to the start procedure where the anode is current limited and the magnet is off. After the magnet current is switched to its nominal value, the transient consists of anode currents as much as 50% greater than the nominal value of 830 mA lasting 300-500 seconds. This behavior persists if the thruster anode discharge is cycled during the time period associated

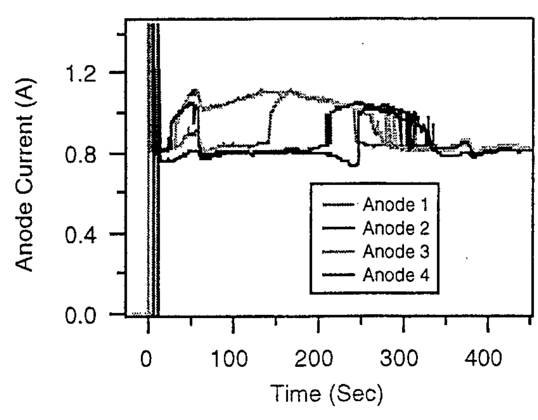

Fig. 6. Anode current start transient with a near simultaneous start of entire cluster during the first firing following exposure to ambient laboratory conditions.

with the anomaly. Interestingly, the thrust level during the period of the anode current transient is unchanged [10]. The 50% increase in anode current simply reduces the efficiency by a like amount.

The behavior during these two modes of operation is distinct. Examination of the time domain behavior of the anode current using two Tektronix TCP202 current probes connected to a TDS3012 100 MHz bandwidth oscilloscope is shown in Fig. 8. Here we see two cases, steady state and the transient. During steady state, there is a strong DC anode current component overlaid by a weak 25 kHz component. The behavior during the anode current transient is nearly the opposite. The anode current is primarily AC with peaks measured as high as 9 A. In this mode of operation, the thruster is literally turning itself on and off every 50-60 μs, approximately 18 kHz.

Through a series of experiments, the cathode has been eliminated as the cause of this behavior. Rather, the cause of this behavior appears to be hydration of the boron nitride (BN) insulator within the acceleration channel. The start transient is believed to be the result of the removal of water molecules from the BN matrix either by heating or sputtering. It is not completely understood how this affects the main discharge as shown in Figs. 5 through 7. Modification of the insulator wall secondary electron emission coefficient, or the introduction of hydrogen into the discharge may account for the transient behavior.

Further information on the transient effect for a single thruster is provided in a companion paper [10]. The transient period exhibits the most clear evidence of electrical cross-talk between independent thrusters. It would appear that the high amplitude oscillations within the various discharges interact during the start transient. However, it is not understood how these oscillations cause the adjoining discharges to enter and exit the high current mode. Further measurements of this phenomena are underway.

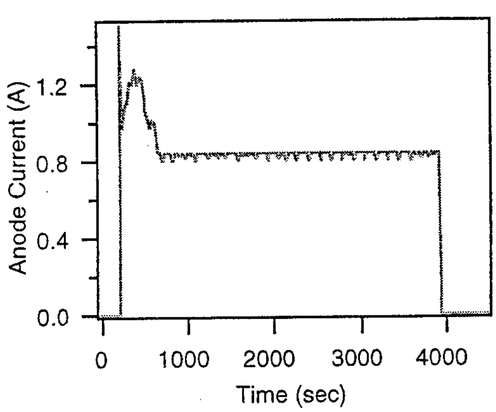

Fig. 7. Anode start current transient characteristic of a single thruster following exposure to atmosphere for several days.

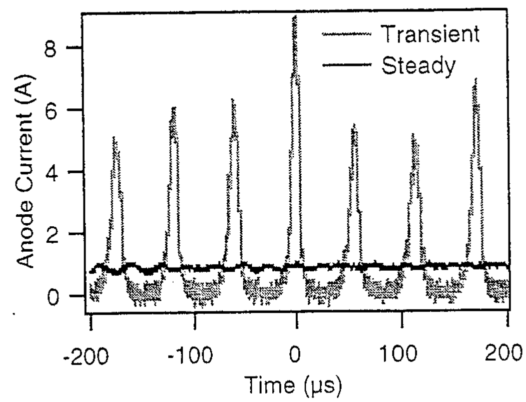

Fig. 8. Anode current oscillations of the transient and steady state cases.

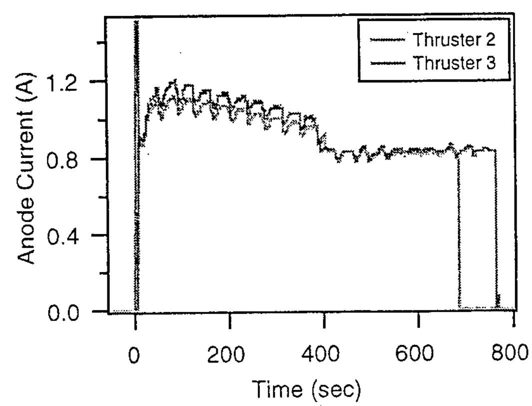

Fig. 9. Anode current trace showing near simultaneous start of thrusters 2 and 3.

Cathode Current Sharing

Figure 9 shows a trace of the anode current of two adjacent thrusters (2 and 3). Unlike the previous cases, here the thrusters have had their cathodes electrically connected to a common ground. The two thrusters exhibit the typical anode current start transient as described previously.

The cathode current, with the keeper and heater return currents subtracted, is shown in Fig. 10. Initially, the two thrusters have not yet been conditioned so the anode currents are higher than their nominal steady state value of approximately 840 mA. The cathode currents mirror their respective anode currents in Fig. 9. That is until approximately 410 seconds after thruster start when the two cathodes momentarily appear to draw near equal currents. Then, at a time corresponding to the entrance of the respective anode currents to steady state conditions, cathode 3 draws approximately 90% of the total anode current. In this instance, cathode 3 is effectively neutralizing both main discharges. At 700 seconds after start, thruster 2 is turned off. Cathode current 3 immediately returns to a nominal value of approximately 830 mA.

Figures 9 and 10 illustrate cathode sharing, or in this case, cathode current stealing. Most of the experimental efforts to date have avoided this issue by the use of independent power supplies for each thruster. In these cases, the cathodes float at slightly different potentials although they are all generally within several volts of one another.

The simplest method to eliminate current sharing between multiple cathodes is to use a single cathode. While the deliberate neutralization of several anode discharges using a single cathode has not been done, Figs. 9 and 10 show that it can be done. An Ion Tech 0.25" cathode has been purchased for continued testing.

In an additional test, the main discharge of thruster 1 was operated with the cathode of adjacent thruster 4. In this test, the cathode 4 experienced poor coupling with main discharge 1. The anode current never went below 950 mA with nominal flow rates. Increasing the cathode flow by a factor of 4 appeared to improve cathode coupling, but only lowered the anode current to approximately 900 mA. It appears that this case is different than that in Figs. 9 and 10 due to the lowered plasma densities in the volume between the cathode and main discharge. The lower plasma density results in a lower conductivity, thus the poor cathode coupling. Increasing the near thruster plasma density would likely improve cathode coupling. This is an especially important point to consider in the design of thruster spacing in a cluster. Although more investigation is needed, this could indicate that neutralizing a large cluster of Hall thrusters with a high flow neutralizer, such as an arcjet, may be advantageous.

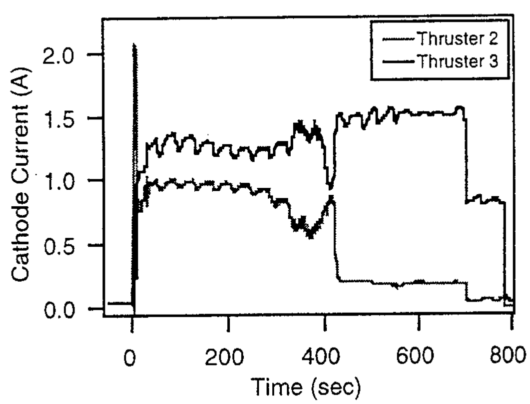

Fig. 10. Cathode current measured concurrently with anode current in Fig. 9. Note that heater and keeper currents have been subtracted from values shown.

Magnetic Field

The magnetic field in the vicinity of the cluster was measured using a model 7030 F.W. Bell 3 axis gaussmeter. The gaussmeter was placed on a three axis translation system with an approximate rectilinear traverse of 30 cm on all axes. Due to the low plasma density outside the thruster acceleration channels, the magnetic field is minimally impacted by the plasma. Therefore, the magnetic field measurements were performed at ambient laboratory conditions with only the thruster magnetic circuits energized. The measurements are presented using a coordinate system as shown in Fig. 11.

Figure 12 shows a contour plot of the Z axis magnetic field component measured in a plane 35 mm from the thruster exit plane. In this plot, we see four features representing the four energized magnetic circuits. The plot resolution is limited by the 20x25 mm spacing of the data but provides an indication of the magnetic field in the near plume region of the thruster.

Figure 13 shows the X-axis component of the magnetic flux along the centerlines of adjacent thrusters 1 and 4 every 2 mm at a position of Z = 25 mm from the exit planes for three cases. In the first and second cases, only magnetic circuit 1 or 4 is energized. In the third case, both magnetic circuits are energized. As expected, the magnetic flux traces in Fig. 13 are geometrically similar. The measurements of the two thrusters simultaneous magnetized is essentially the

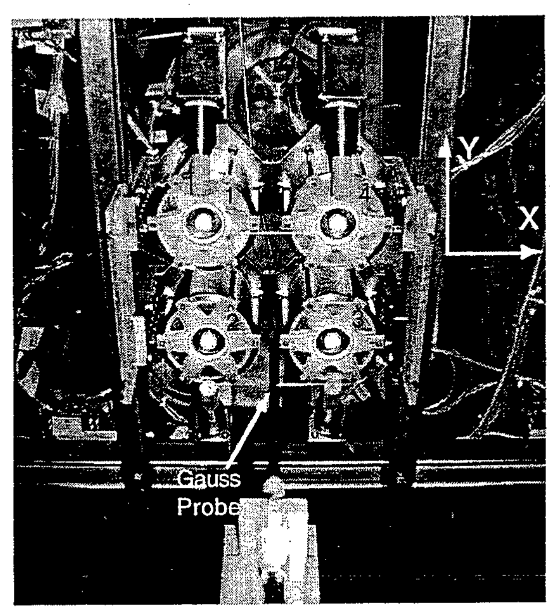

Fig. 11. Magnetic probe and traversing stages shown within vacuum chamber. Z axis is parallel to probe body in the direction of ion travel.

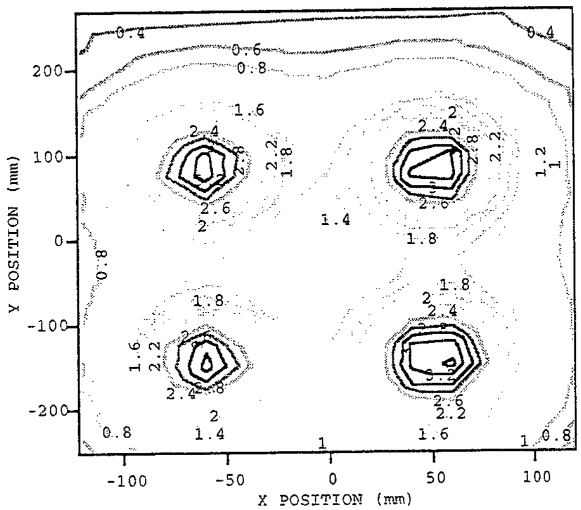

Fig 12. Contour plot of Z component of the magnetic flux (G) taken in a plane 35 mm from cluster exit planes.

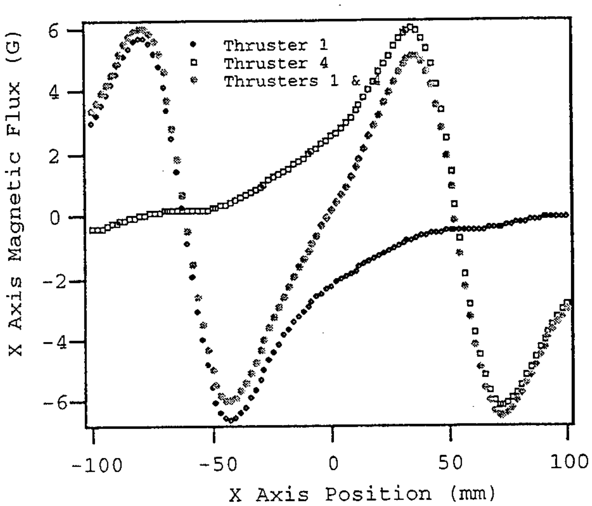

Fig. 13. X axis magnetic flux at Z = 25 mm across the center of thrusters 1 and 4 measured for thrusters 1 and 4, individually and simultaneously magnetized

linear superposition of the two individual cases as predicted from electromagnetic theory [15].

The magnetic and electric fields are related through Ohm's law which states that the electric field is the product of the plasma conductivity and the magnetic field [16].

$$\vec{E} = \sigma\vec{B} \qquad (1)$$

Where $\vec{E}$ is the electric field, σ is the plasma conductivity, and $\vec{B}$ is the magnetic field. Although the conductivity is a function of the electron temperature and density, the assumption that the plasma conductivity does not vary greatly in the low density plume is a reasonable first order approximation. Therefore, the traces in Fig. 13 can also be taken to be representative of the electric fields for each respective case.

Figure 13 may then hold the key to understanding the higher than expected flux of two simultaneous firing thrusters shown in Fig. 5. These two cases are in form analogous, and together illustrate how the thruster plumes appear to interact. The simultaneous firing of thrusters modifies the magnetic fields in the near plume region. This in turn produces a modification of the near plume electric field, particularly in the region between the thrusters. The modification of the near plume field then presumably modifies the divergence of the combined plumes by the small amounts shown in Fig. 5. This is further illustrated in Fig. 14 where the traces in Fig. 13 are integrated to show the behavior of local plasma potentials.

Future plume tests to quantify this effect are in progress whereby a thruster will be operated with and without the magnetic circuit of an adjacent thruster energized at both positive and negative polarities. This experiment will determine whether the above thesis has merit, and if so, quantify the effect.

Understanding the behavior of the magnetic circuit is important for clustering. Due to the relatively low plasma densities in the plume, magnetic fields strongly determine the electric fields which govern the flow of the charged plume particles. Therefore, small changes in the magnetic field strengths near the thruster can affect the down stream plume behavior. These measurements indicate that in order to understand the apparent narrowing of the plume for multiple thrusters, measurements of the near field magnetic field need to be coordinated with further plasma parameter measurements. Together these measurements will provide a quantitative measure of the effects of thruster placement.

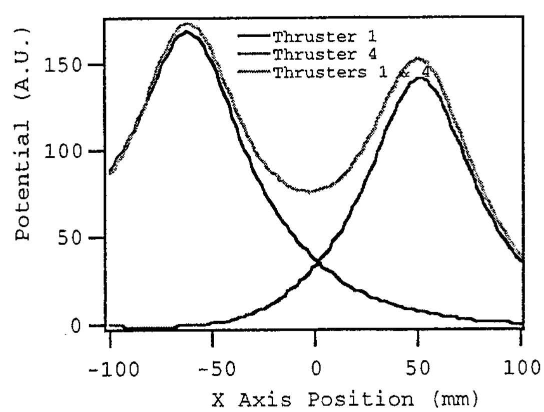

Fig. 14. Electric Potentials calculated by integration of the B field data in Fig. 13.

Conclusions

These measurements represent a series of preliminary measurements on a cluster of four 200 W BHT-200-X3 Hall thrusters. These measurements are aimed at understanding the engineering issues associated with operating a number of Hall thrusters in close proximity.

Faraday probe measurements have been taken to gain a measure of plume interactions. Ion current densities of single plumes were measured and compared to the plume of two simultaneously operating thrusters. These initial results appear to indicate that the plume of two thrusters is slightly less divergent than that expected by the linear superposition of the individual plumes. This result is preliminary and issues related to the use of a Faraday probe require further exploration.

The greatest interaction of independent thrusters within the cluster appears to occur during initial start-up after thruster exposure to atmospheric, or regenerated, water vapor. During the high anode current transient period, the thrusters of the cluster randomly enter and exit a high anode current mode. Further, the thrusters occasionally appear to be linked as they enter and exit the high anode current mode. This is contrasted with the single thruster transient where the thruster anode current gradually transitions to a steady state anode current of 820-840 mA. In all cases, the anode current transient is characterized by a high frequency (~18 kHz) on/off behavior in the main discharge which appears to increase the average plasma conductivity through the radial magnetic field, thus increasing the time averaged anode current.

Cathode current sharing is examined in a pair of adjacent thrusters. When two cathodes were tied to a common ground, one cathode would dominate the emission current and in the case examined, the dominant provided 90% of the combined current. When a main discharge was coupled to an adjacent thruster's cathode, the coupling was poor with approximately 15% higher than normal anode current. It is believed that a higher plasma density in the intervening volume between a cathode and distant discharge chamber will improve due to increased plasma conductivity. This implies that larger clusters of Hall thrusters will require either isolated cathodes for each component thruster, or common neutralizers with high flow rates, such as arcjets.

It is important to note that once the thrusters are conditioned and if the cluster is electrically unconnected, no significant interaction is observed. At this time, the operation of clusters of independent thrusters appears to be the simplest implementation. Future efforts will examined the interactions between the main discharges implied by the start-up behavior which are assumed to continue to a lesser degree into steady state operation.

A number of magnetic field measurements with the thrusters off were taken in the laboratory. These measurements are important to understanding the effects of adjacent thrusters during operation. The electric fields near the thruster exit are to a great extent determined by the magnetic fields. Measurements performed in this study imply that magnetic fields of adjacent Hall thrusters can affect the plume expansion. Further measurements are required to quantify these effects.

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